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Simulation of the Taiwan Climate Using the Hadley Centre PRECIS Regional Climate Modeling System: The 1979 - 1981 Results

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ABSTRACT

In this paper we describe the simulation of Taiwan's climate for the period 1979 - 1981 using the Hadley Centre PRECIS (Providing Regional Climates for Impact Studies) regional climate modeling system. The PRECIS simulations of surface precipitation and temperature have been compared in detail with the Central Weather Bureau measurements, and also with outputs from the IPCC global climate models such as the HadCM3, the CCSR, and the NCEP 50-year reanalysis data. Our results show that the very complicated spatial patterns of surface rainfall as revealed from the measurements can only be reproduced using the PRECIS model. The inter-annual variability in rainfall has shown to be well reproduced by the PRECIS model. The PRECIS model also demonstrates a good capability in simulating the spatial distribution of surface temperature over the whole of Taiwan, especially over Taiwan's Central Mountain Range. Since the PRECIS simulations were produced in combination with the ERA-15 global model results, our results show that a good way forward in conducting regional climate modeling at the national level requires the use of both global climate models and high resolution regional climate models.

(Key words: Regional Climate, PRECIS, Climate Model, Climate Simulation, Taiwan's Climate)

1. INTRODUCTION

Simulating climate change at the regional and national levels is essential for policy mak-

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ing (Burroughs 2003). There is a growing recognition now of the urgent need for detailed climate knowledge over the Taiwan area (e.g., Hsu and Chen 2002), as the society appears to be more prone to the effects brought about by changes in the climate especially increasing temperatures and reliable rainfall (Collier and Webb 2002). For example, in recent years Taipei's Feitsui Reservoir has been severely depleted owing to a lack of rain. This depletion led to alternate day water restrictions in the Taipei metropolitan area, and ironically such restrictions came in the two years post the record breaking rainfall brought by the Typhoon Nari in 2001 (Sui et al. 2003; Wang et al. 2004). Another area of apparent change has been in seasonal ground-level temperatures which can impact significantly electric power usage, the spreading of disease, and other health-related issues (Martens 1998; Kaiser 2002). The ground-level temperature in Taiwan has been shown to have experienced an island-wide warming of 1.0° - 1.4°C over the past 100 years (Hsu and Chen 2002). Climate change in Taiwan is an actuality the impacts of which the people of Taiwan now have to come to terms with. It is not difficult to foresee a time when the significance of climate change will be a daily concern of the people and government of Taiwan.

Studies of Taiwan's climate have relied mainly on analysis of the past 100 years or so of surface meteorological measurements collected by a network of the Central Weather Bureau's (CWB) meteorological stations (http://www.cwb.gov.tw). As informative as this data is in presenting overall characteristics of surface temperatures and precipitation patterns in Taiwan for the past 100 years, analysis of the CWB data alone does not reveal insights into the mechanisms responsible for the ups and downs of temperatures and precipitations exhibited in the time series curves of these parameters. It is very unlikely that we will ever really be certain about what has happened in the past if we are not able to reconstruct (hindcast) the climate for the past 100 years, let alone forecast the future Taiwan climate.

Recent attempts have been made to go beyond the constraint of station weather data analysis by introducing the use of global climate model outputs such as those from the IPCC climate models to study regional climate in the East Asia region (Hsu and Chen 2002). This effort clearly indicates that Taiwan urgently, if not desperately, needs to know its own past climate processes (by hindcasting) in order to build modeling capacity that will assist in predicting its own future climate, one potentially plagued by increased concentrations of greenhouse gases and other ambient pollutants.

The main purpose of this work is to conduct a detailed comparison of the IPCC global climate model results with the CWB measurements. And, most importantly, we compare the IPCC results and the CWB measurements directly with the latest implementation of the Hadley Centre PRECIS regional climate model (Hulme et al. 2002; Jones et al. 2003; Huntingford et al. 2003). The comparisons of the IPCC model results over the East Asia region have been reported in Hsu and Chen (2002). Here we compare the IPCC global model outputs with the time series measurements of surface temperatures and precipitation at several locations in Taiwan. The comparison of the PRECIS regional climate simulations with the CWB measurements and the IPCC model results will demonstrate how effective high-resolution climate models employed in modeling Taiwan climate can be.

2. DATA AND MODELS

2.1 The Central Weather Bureau Data

The meteorological data used in this work is obtained from a network of surface meteorological stations (Fig. 1a), and automated surface raingage stations (Fig. 1b). There are 23 surface meteorological stations, and more than 350 raingage stations. Some of the meteoro-

(a)

(b)

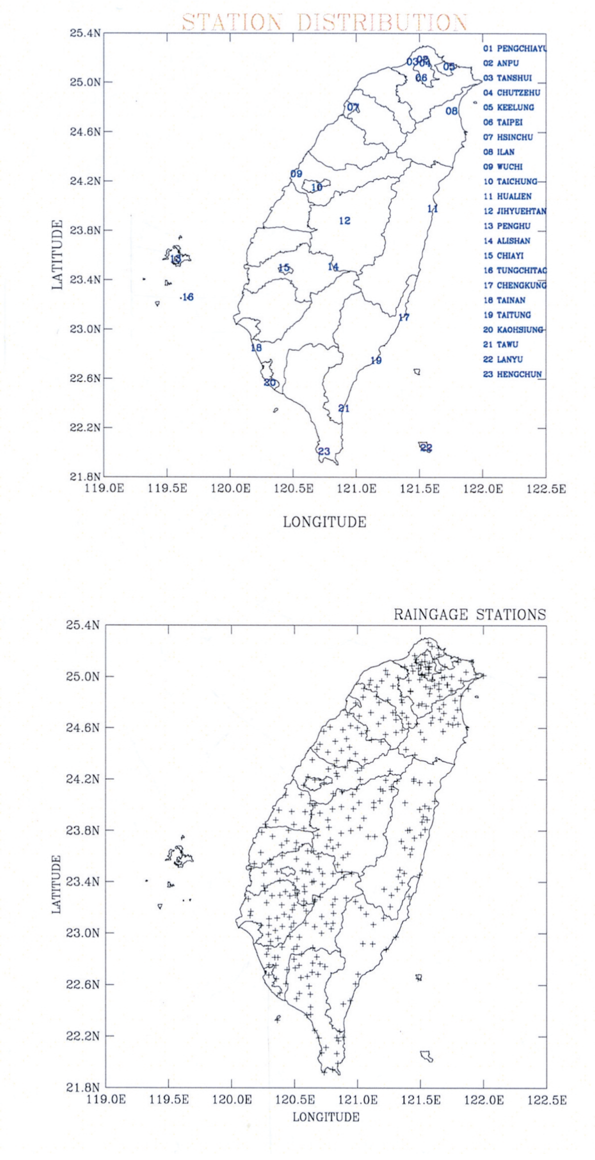

Fig. 1. Spatial distribution of the Central Weather Bureau surface meteorological stations (a), and the automatic raingage stations (b).

logical stations such as Taipei (station number 6), Taichung (10), and Heng-Chun (23) contain a century of records of surface temperature and precipitation. Most of these stations have records that last for at least half a century. The CWB has also maintained a very high density of surface raingage stations over Taiwan. This impressive array of surface raingage stations has provided very high temporal and spatial resolution of precipitation measurement over Taiwan since the early 1990s.

2.2 The Hadley Centre PRECIS Model

The Hadley Centre PRECIS regional climate modeling system is used in this work. The model is based on HadAM3H, an improved version of the atmospheric component of the latest Hadley Centre coupled AOGCM, HadCM3 (Gordon et al. 2000; Jones et al. 2004). The PRECIS has been used with horizontal resolutions of 50 and 25 km with 19 levels in the atmosphere (from surface to 30 km in the stratosphere) and four levels in the soil. One key approach taken by the Hadley Centre in developing climate models is the use of the same representations of both grid scale dynamical and sub-grid scale physics in both global and regional models. The aim of this approach is to ensure that the same dynamics and physics are consistent and used in producing high solution climate projections from the large-scale projections of the global models (Jones et al. 2004).

A full description of the PRECIS regional climate model is given in Jones et al. (2004) and the references therein. Following Jones et al. (2004), the atmospheric component of the PRECIS model is a hydrostatic version of the full primitive equations. The model uses terrain-following σ-coordinates (σ = pressure/terrain pressure). The model equations are solved in spherical polar coordinates and the latitude-longitude grids are rotated so that the equator lies inside the region of interest in order to obtain quasi-uniform grid box area throughout the region. An Arakawa B grid (Arakawa and Lamb 1977) is used for horizontal discretization. Fourth horizontal diffusion is applied everywhere (except the top where second order diffusion is applied) to the wind and thermodynamic variables.

For convective parameterization, the model uses a mass flux penetrative scheme (Gregory and Rowntree 1990) with an explicit downdraught (Gregory and Allen 1991) and includes the direct impact of vertical convection on momentum, heat, and moisture (Gregory et al. 1997). The evaporation of convective precipitation is accounted for. Convective precipitation within a grid box is assumed to fall on 65% of the land surface, regardless of convective cloud fraction. The threshold values of cloud liquid water for precipitation are $2\ \mathrm{g\,kg^{-1}}$ over land and $0.4\ \mathrm{g\,kg^{-1}}$ over sea. For large-scale precipitation, the model calculates critical relative humidity (which represents the threshold point for the formation of cloud) for each grid box at every timestep. Cloud water is assumed to be liquid above 0°C frozen below -9°C and a mixture in between. The threshold values of cloud liquid water for precipitation formation are 1.0×10^{-3} ($\mathrm{kg\,kg^{-1}}$) over land and 2.0×10^{-5} over sea. The evaporation of large-scale precipitation is accounted for. Large-scale precipitation within a grid box is assumed to fall on 75% of the land surface.

The radiation scheme computes time-varying insolation, short-wave (6 bands), and long-wave (8 wave bands) fluxes following the evolution of the temperature, water vapor, clouds (liquid and frozen water, respectively), and greenhouse gases such as ozone, carbon dioxide, nitrous oxide, methane, CFC11, and CFC12. In the boundary layer, a first order turbulent mixing scheme is used to vertically mix the conserved thermodynamic variables and momentum (Smith 1990), and the MOSES land surface scheme (Cox et al. 1999) is used for modeling land surface processes. The gravity wave drag of Palmer et al. (1986) is applied to momentum components in the free atmosphere.

The PRECIS model has been used in regional climate modeling in the UK and over Europe (Jones et al. 1995; Jones et al. 1997; Noguer et al. 1998; Bhaskaran et al. 1998; Durman et al. 2001). Figure 2 shows the model domain used in the work. The entire model domain

(a)

(b)

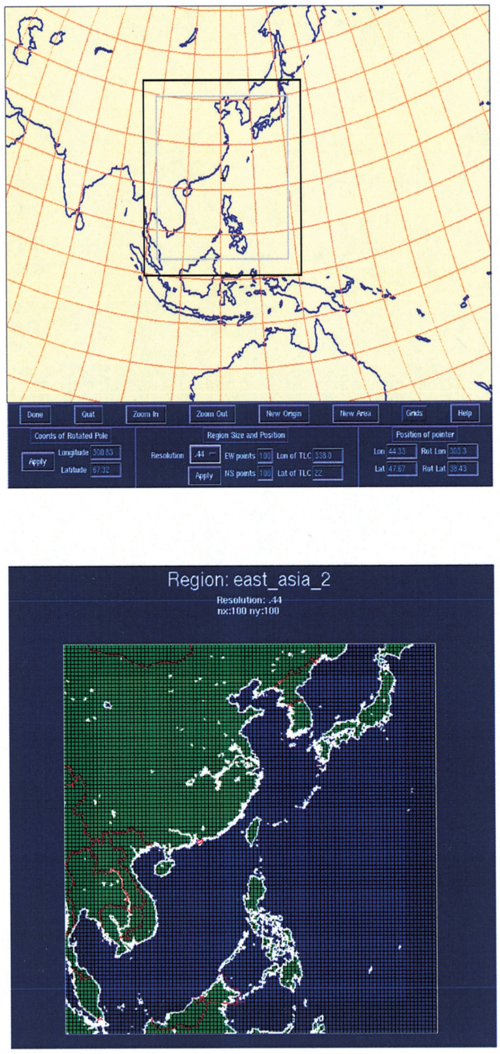

Fig. 2. The experimental setup of the domain (a), and the land-sea mask (b) of the Hadley Centre PRECIS regional climate model used in this work.

consists of an array of 40000 (200 by 200) grids with a 0.44° × 0.44° latitude/longitude grid resolution, giving a spacing of 50 km at the equator (Jones et al. 2004). Due to this fine resolution, the model uses a timestep of 5 minutes to maintain numerical stability.

Figure 3b shows the distribution of the PRECIS model grids over the Taiwan region. The initial conditions for this work are taken from the European Medium Range Weather Forecast (ECMWF) reanalysis data, which also provides 6-hourly lateral boundary conditions. The

(a)

(b)

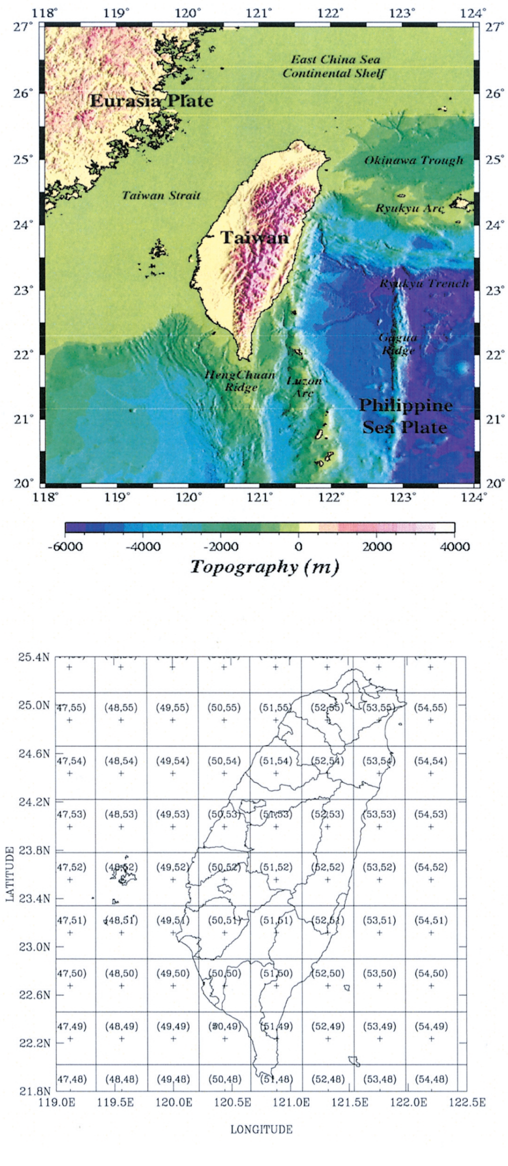

Fig. 3. Taiwan topography (a), and the PRECIS grid boxes over Taiwan area (b). (Source of the topography map: dmc.earth.sinica.edu.tw)

model was initiated on 1 December 1978, and run continuously until the end of November 1981. Jones et al. (2004) suggested that the spin-up for the atmospheric component of the PRECIS should take a few days, while the land-surface model may take one or more annual cycles to come into equilibrium with the atmospheric forcing. Hence, they recommend one year for the PRECIS to spin up. In this work we integrate the PRECIS model continuously for three years. We discuss all three years' results in section 4.

2.3 The IPCC Climate Models

Global climate models are the backbone of climate impact studies as shown in the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2001). As the resolution in the global climate models is increased it is possible to provide more detailed representations of atmospheric processes and important phenomena (Burroughs 2003). A global model at T21 configuration has a horizontal resolution of 500 km, T42 has a resolution of 250 km, T63 has a resolution of 180 km, and T106 has a resolution of 110 km. A global climate simulation at T106 configuration requires a tremendous amount of computational resources to complete. As such, only institutes and countries with large computational resources [for example, the Earth Simulator (Ohfuchi et al. 2004)] are capable of conducting global climate modeling at high (e.g., T106) resolution. However, even at a configuration as high as T106, the 110 km resolution is still too coarse for Taiwan. Another issue is that the climate model outputs available to the scientific users are generally prepared at coarser resolutions than the original high-resolution models that produce the results. Figure 4 shows a 2.5° by 2.5° degrees global grid system

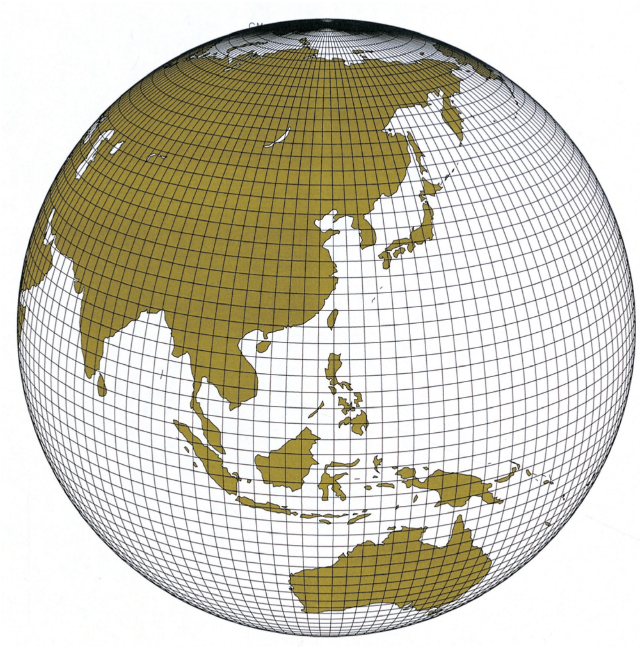

Fig. 4. A typical 2.5 × 2.5 grid system used in the global climate models.

over the East Asia region. This is one of the most frequently used grid systems in the global analysis datasets such as NCEP 50-year reanalysis data (Kalnay et al. 1996) and the ERA-40 reanalysis data (Simmons and Gibson 2000).

Figure 5 shows the distributions of model output grids over the Taiwan region from the NCEP analysis data (temperature and precipitations, respectively), the Hadley Centre Climate Model, HadCM3 (Gordon et al. 2000), and the University of Tokyo's Center for Climate System Research (CCSR) climate model (Emori et al. 1999). Notice that the grid resolutions shown here for the HadCM3 and CCSR models are based on the data available at an IPCC inventory (http://ippc-ddc.cru.uea.ac.uk). The actual model grid resolutions are higher than the reduced output grid resolution. Figure 6 shows the distributions of output resolutions from the Meteorological Service of Canada climate model (CGCM2), the Australian Bureau of

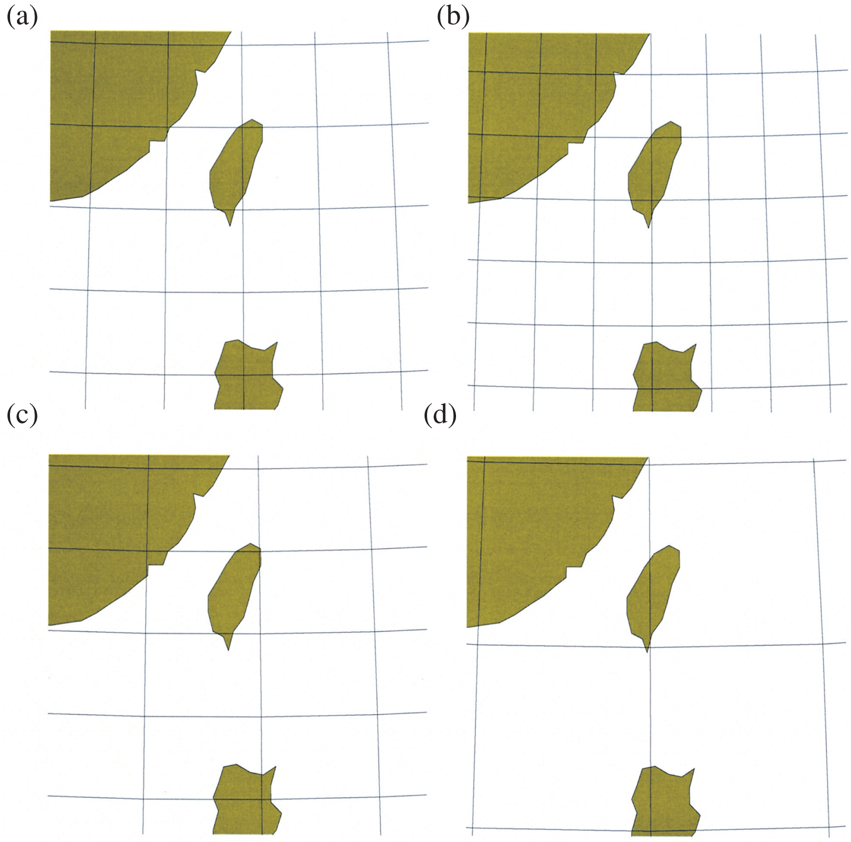

Fig. 5. The grid size for (a) the NCEP reanalysis of surface temperature at a $2.5° \times 2.5°$ resolution (a total of 144×73 grid points), (b) the NCEP reanalysis of surface precipitation at a T62 resolution (a total of 192×94 grid points), (c) the HADCM3 model at a $3.5° \times 2.5° \times$ L19 longitude-latitude-level resolution (a total of 96×72 grid points), and (d) the CCSR model at a T21L20 resolution (a total of 64×32 grid points).

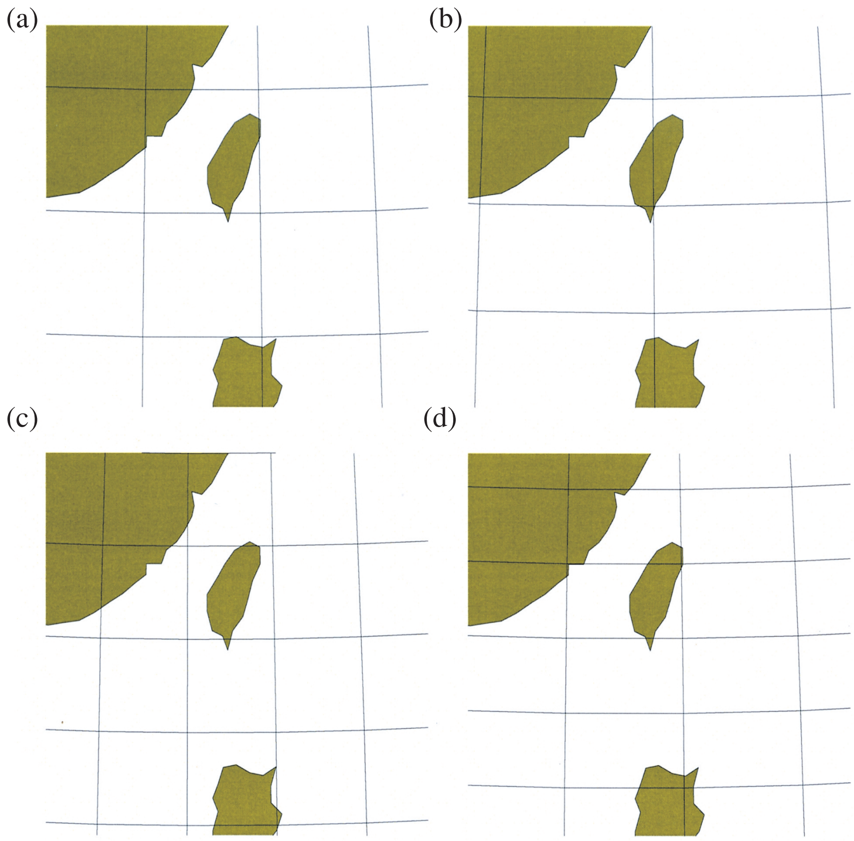

Fig. 6. The grid size for (a) the CGCM2 model at a T32L10 resolution (a total of 96 × 48 grid points), (b) the CSIRO model at a R21L9 resolution (a total of 64 × 56 grid points), (c) the ECHAM4 model at a T42L19 resolution (a total of 128 × 64 grid points), and (d) the GFDL model at a R30L14 resolution (a total of 96 × 80 grid points).

Meteorology climate model (CSIRO), the German Max Planck Institute climate model (ECHAM4), and the Princeton University Geophysical Fluid Dynamics Laboratory climate model (GFDL). These figures demonstrate that the output grid resolutions from the IPCC global climate models contain a range of 2 to 4 grids over the Taiwan area.

In the following section, we present results of the PRECIS simulations of Taiwan's climate for the period 1979 - 1981, and compare PRECIS results with the data from IPCC models (CCSR/NIES and HadCM3) and a reanalysis dataset (NCEP) for the same period. The comparisons are made in both time-series and two-dimensional (2-D) format. For the time-series comparison, we chose three major cities as the representative sites of the north (Taipei), central (Taichung), and south (Kaohsiung) of Taiwan. Figure 1a shows the geographical locations of these three sites (index 06 for Taipei, 10 for Taichung, and 20 for Kaohsiung). The hourly observed data at these sites are accumulated as the monthly rainfall, while the surface temperatures are averaged as the monthly mean temperature. The corresponding modeled data at a site is judged based on finding a model grid box that contains the location of this site. Figure 3b shows distribution of model grid boxes over Taiwan area for the PRECIS model. Figure 5 shows distribution of model grid boxes from the NCEP reanalysis data, the HadCM3 model, and the CCSR model, respectively. For the 2-D comparison, both modeled data and observed data over Taiwan are taken and re-analyzed into a 1 km by 1km grid resolution using the objective analysis method of Deutsch and Journel (1992).

3. RESULTS

3.1 Time Series Precipitation in Taipei (North Taiwan)

Figure 7 shows time series plots of monthly-accumulated surface precipitation measured in Taipei for the period between December 1978 and November 1981. Also shown in the plots is the modeled precipitation from the PRECIS model, the NCEP reanalysis data, the HadCM3 model, and the CCSR model. The measurements show that overall precipitation in 1980 appears to be lower than that measured in 1979 and in 1981. Heavy precipitation (> 400 mm month^{-1}) is recorded in June and in August of 1979, and during May to July of 1981. Less intensive rainfalls appear during the autumn to winter seasons. However, there are strong year-to-year variations with respect to the months with lowest rainfall.

The PRECIS model appears to be making a close simulation when compared with the measurements in Taipei. For example, the measured low rainfall in 1980 and the high rainfall in 1979 and 1981 are generally reproduced by the model. This inter-annual pattern is characteristically reproduced in the NCEP reanalysis data as well, though the overall precipitation from the NCEP is much lower than the measurements. The HadCM3 model shows a slightly higher precipitation in 1980 than in 1979 and in 1981, while the CCSR model shows a lower rainfall in 1979 than in 1980 and in 1981. Hence, when comparing measurements, the inter-annual variability in surface precipitation is much better reproduced by the PRECIS model than by the other global climate models (HadCM3 and CCSR). Even the NCEP reanalysis data produces a less realistic rainfall distribution than the PRECIS results.

Another important aspect in evaluating the performance of climate models is how the model predicts extreme events, such as wet and dry months, in comparison with the measurements. Although the length of the integrations conducted in this work last only 36 months, there are already several pronounced peaks (wet) and lows (dry) shown in the measurements. For example, the monthly rainfall in August 1979 is close to 500 mm. This number goes down to close to a few tens of millimeters two months later, in October 1979. Even rainfalls in August are not always the same for different years. The monthly rainfall in August 1980 is less than 300 mm and in August 1981 the rainfall is less than 50 mm.

The PRECIS model shows simulated rainfall with peaks and lows that more closely resemble the measurements than the global climate models. The largest discrepancies appear in July 1981 when the model is too dry, and in August-September 1981 when the model is too

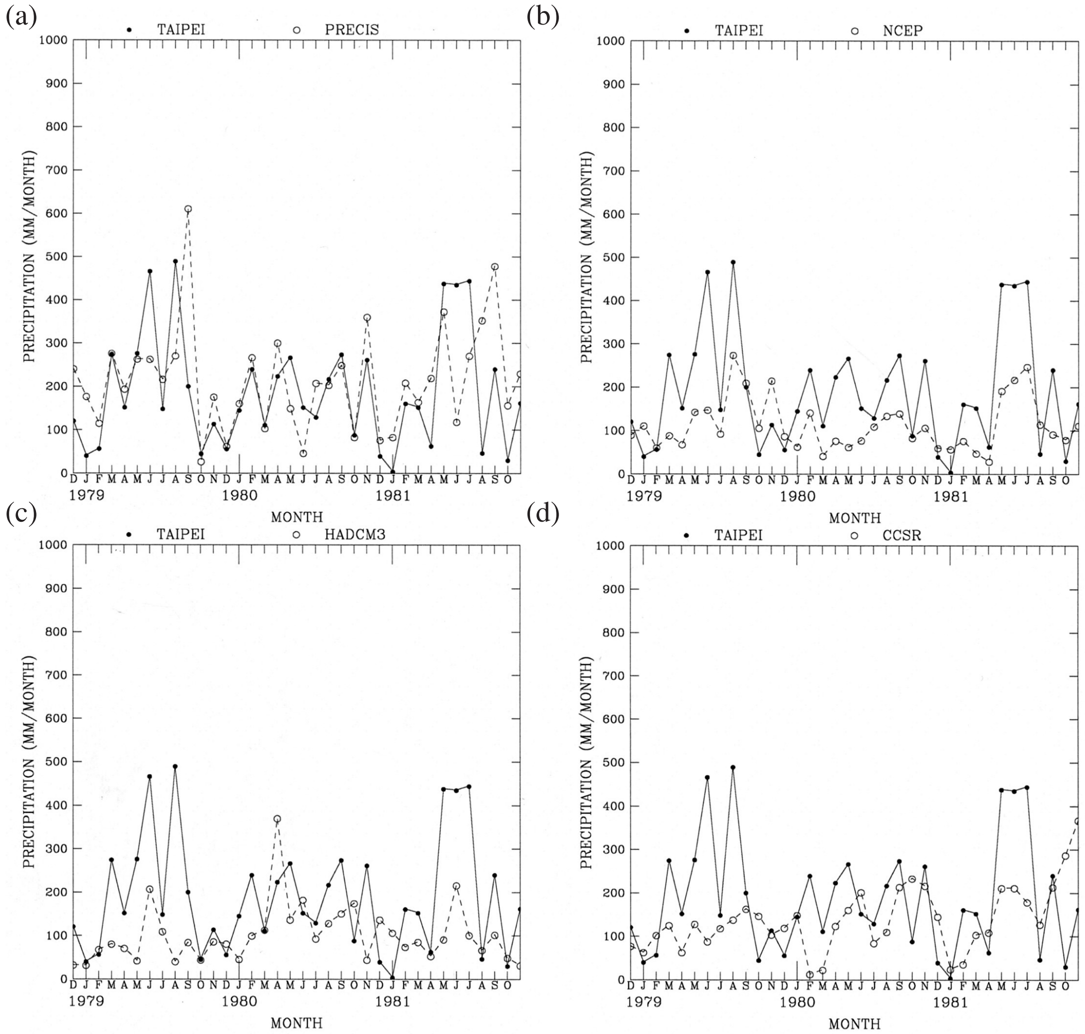

Fig. 7. Measured (solid circles) and modeled (open circles) time series plots of monthly accumulated surface precipitation in Taipei for the period between December 1978 and November 1981. The modeled results are from PRECIS (a), NCEP (b), HADCM3 (c), and CCSR (d).

wet compared with the measurements. The PRECIS simulation in 1980 is actually quite promising when compared with the measurements.

3.2 Time Series Precipitation in Taichung (Central Taiwan)

Figure 8 compares time series plots of surface accumulated precipitation measured in

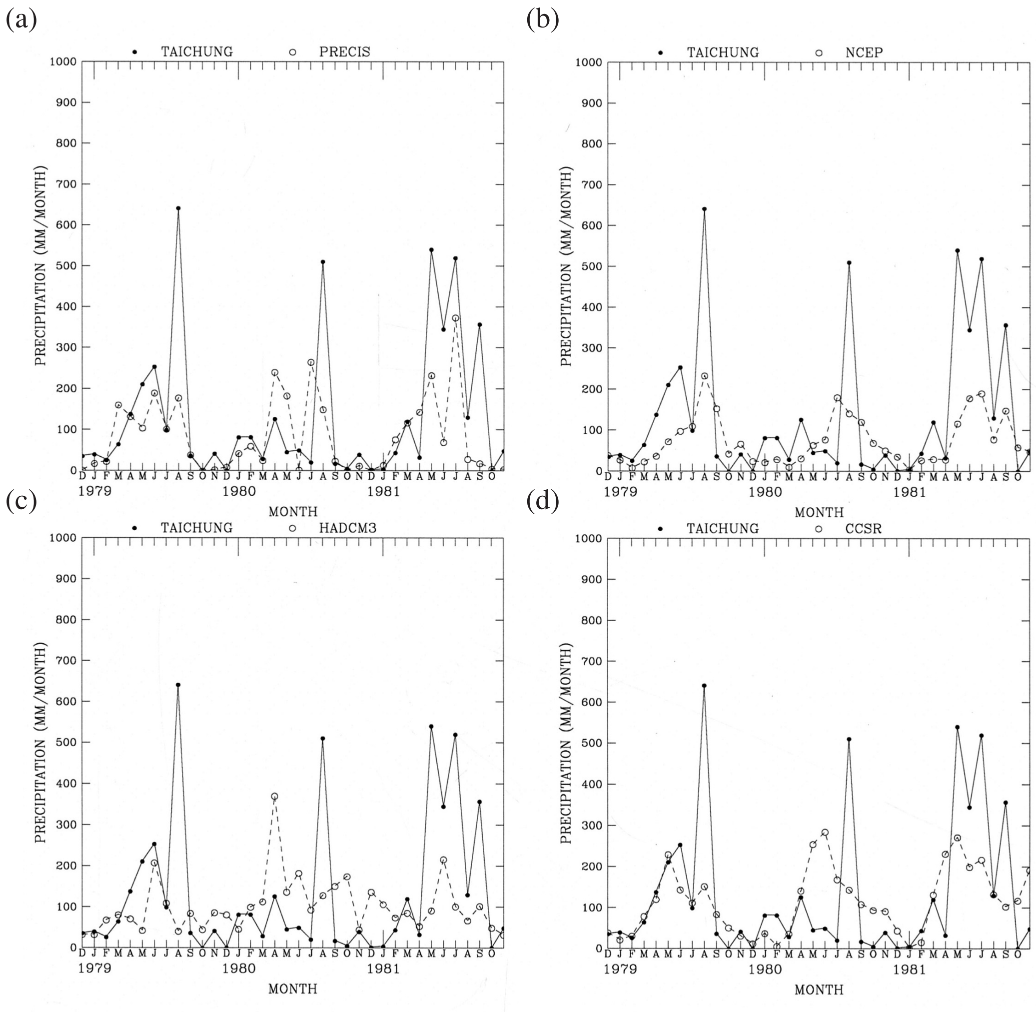

Fig. 8. The same as in Fig. 7 but for Taichung.

Taichung to those calculated by the models. Taichung is located in the central part of Taiwan (Fig. 1), and the monthly rainfall shows a distinctive pattern unlike that measured in Taipei (Chen and Chen 2002). Precipitation seems most intense in the summer months and to be greater than in the Mei-Yu (Plum Rains) season (e.g., Chen and Chen 2002; Chen et al. 2003). However, this rule of thumb is not really applicable throughout these three years. For example, August 1981 is dry compared with the previous two years, while June 1981 is very wet compared with the same month in 1979 and 1980. Figure 8 shows three distinctive periods of elevated rainfall, and the dry season that normally appears during November, December, and January. The PRECIS model in general reproduces these three periods of elevated precipitation and the intervening dry periods. The heavy rainfalls in August are underestimated in all three years. The NCEP reanalysis data shows a pattern that qualitatively resembles those of the observed patterns. The HadCM3 appears to produce more rainfall in the winter dry months while underestimating rainfall in the summer. The CCSR model underestimates rainfall in summer, and overestimates rainfall in May - June of 1980.

3.3 Time Series Precipitation in Kaohsiung (South Taiwan)

Comparisons of time series plots of measured surface rainfall with model calculations are shown in Fig. 9 for Kaohsiung. This location is further south than Taichung, and is tropical (Fig. 1). The measurements reveal three distinctive periods of intense rainfall (wet season) from late spring to late summer. The dry season in Kaohsiung is between October and February;

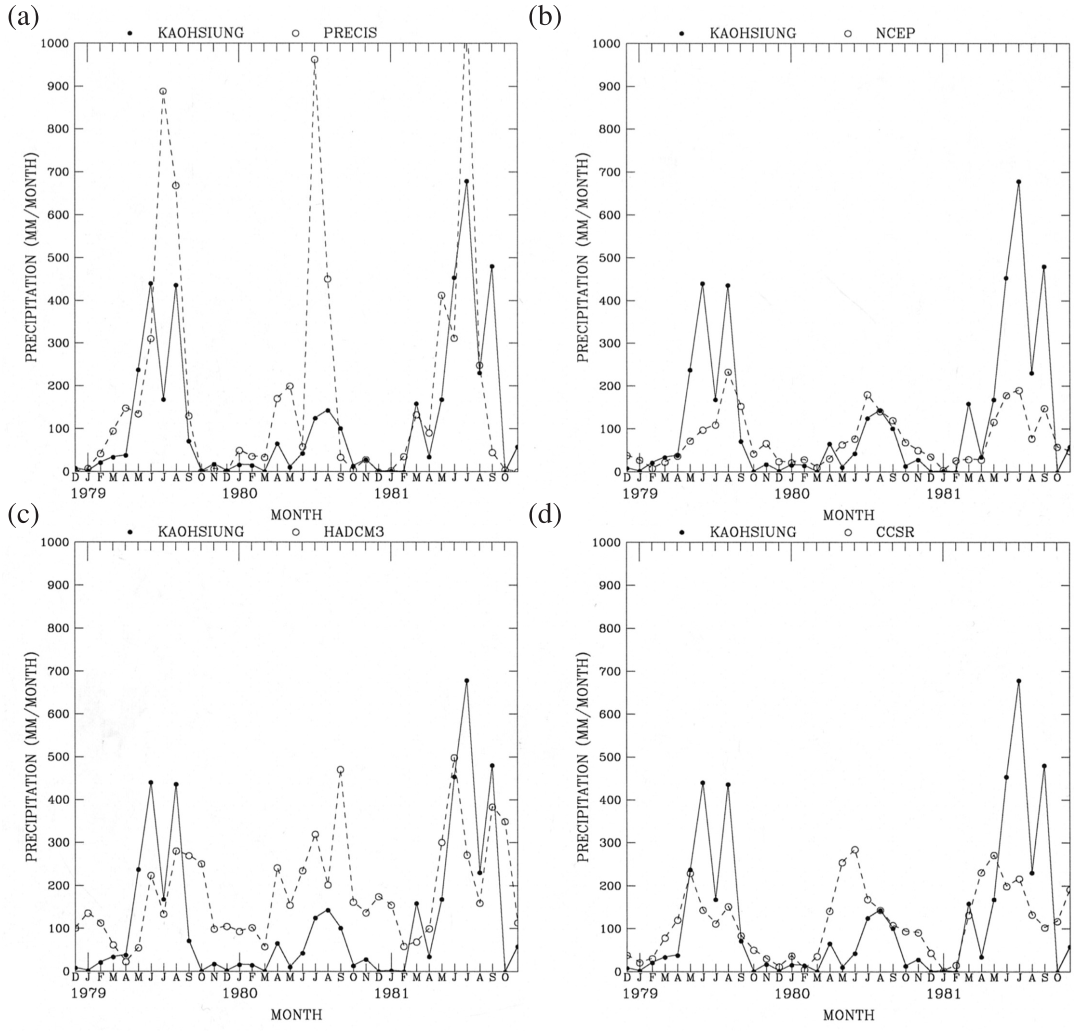

Fig. 9. The same as in Fig. 7 but for Kaohsiung.

and the distinction between wet and dry seasons is pronounced. In this respect, a comparison of all three locations would have Kaoshiang as having more distinct wet and dry seasons than Taichung, and these two cities in turn having more distinct wet and dry seasons than Taipei. The biggest influencing factor here is that of the winter monsoon which impacts the north of Taiwan where Taipei is located (Chen and Chen 2003).

The PRECIS model calculates rainfall patterns in Kaohsiung that resemble but overestimate those shown in the measurements. On the other hand, the NCEP reanalysis underestimates rainfall in 1979 and in 1981, but does quite well in 1980. The HadCM3 overestimates rainfall in 1980 but underestimates it in the other two years. The winter dry season is not reproduced in the HadCM3 model with predictions being too wet for southern Taiwan winters. Interestingly, the CCSR calculates annual maximum rainfall during the spring season of May to June instead of from June to August.

3.4 2-D Distribution of Precipitation in Taiwan

One of the very important tasks in modeling Taiwan's climate is the reproduction of spatial and temporal variation in surface precipitation patterns contained in field measurements. As clearly shown in Fig. 1b, Taiwan maintains one of the densest arrays of surface raingage stations in the world. The annual rainfall in Taiwan is about 2500 mm per year. As such, Taiwan is very well positioned to conduct regional climate modeling and verify quantitatively regional climate model reproductions of surface rainfall against field measurements. Success in this area would have important implications for scientific research and practical societal applications.

Figure 10 shows PRECIS simulations of surface rainfall distributions for January 1979, 1980, and 1981, respectively. Also shown in the figure is surface rainfall distribution from the NCEP reanalysis data, the HadCM3 simulations, the CCSR simulations, and climatology (based on 1992 - 2002 measurements). Global climate model limitations in simulating Taiwan's climate are evident when comparing the results of global modeling with the PRECIS calculations and field measurements. The extremely complicated, inhomogeneous surface rainfall distributions revealed by the field measurements can only be resolved in the PRECIS calculations. Main rainfall characters such as its elevation along the northern edge of Taiwan due to that being the windward side of the winter monsoon, and drier areas in southwestern Taiwan (Chen and Chen 2003) are both reproduced by the PRECIS model.

PRECIS simulations of rainfall distribution for February, March, and April have been systematically compared with field measurements and other global models (not shown here). These comparisons indicate that the PRECIS model is simulating rainfall distribution in Taiwan that closely resembles the measurements, a result consistent with that presented in Fig. 10. As Taiwan enters the Mei-Yu (Plum Rains) season, the field data indicates enhanced precipitation over the mountain regions (Fig. 3a), for example, Ilan (northeastern Taiwan), and more rainfall in the south than in the north (Chen and Chen 2003). The PRECIS calculations (not shown here), and HADCM3 model also generally exhibit this same trend; the CCSR model is consistent with the field measurements with greater rainfall in the south than in the north.

For June (1992 - 2002) more rainfall persisted over the mountain regions, and to the south; the strength of this precipitation was generally higher than for the previous months. However, the most important feature revealed is the distinctively dry June in 1980 compared with the wet Junes of 1979 and 1981 predicted by the PRECIS model (not shown here). As

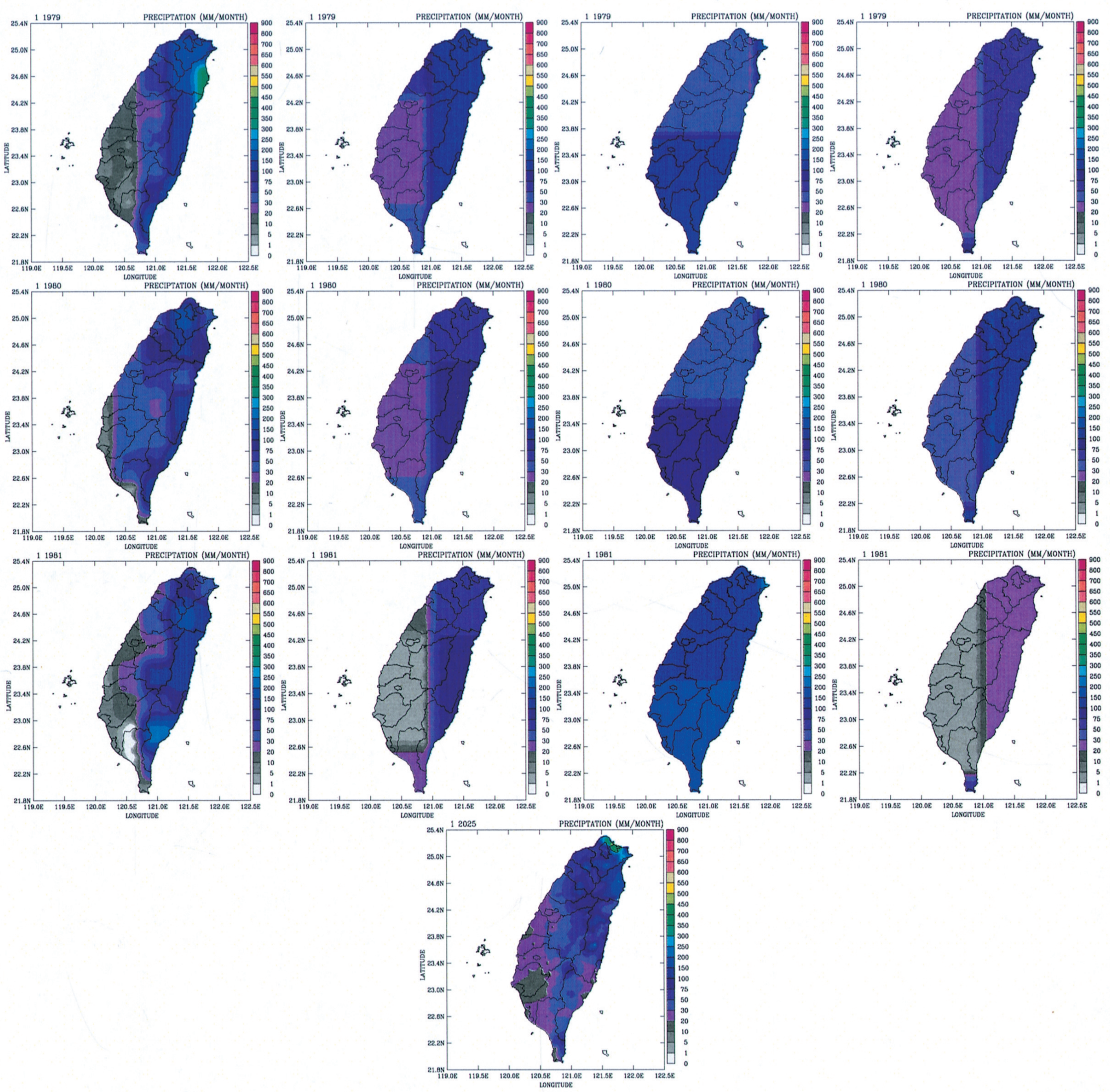

Fig. 10. The PRECIS simulations of surface rainfall distributions in January of 1979, 1980, and 1981, respectively (plots in the 1st column from left). Also shown in the figure are the surface rainfall distribution from the NCEP reanalysis data (2nd column to the left), the HadCM3 simulations (3rd column to the left), the CCSR simulations (4th column to the left), and the climatology (lowest panel).

confirmed in Fig. 7, the June of 1980 at the three locations of Taipei, Taichung, and Kaohsiung has low rainfall compared with the same months for 1979 and 1981, when intensive rainfalls occurred. This demonstrates that the important inter-annual variability in rainfall was reproduced well by the PRECIS model. This is a very important capability for climate modeling and forecasting. More modeling studies, however, are required to demonstrate if the PRECIS model can consistently perform well in reproducing inter-annual rainfall variability for Taiwan.

Figure 11 shows rainfall distributions in July from the field data and models. The PRECIS model shows enhanced rainfall in both southern, and western parts of Taiwan. This pattern

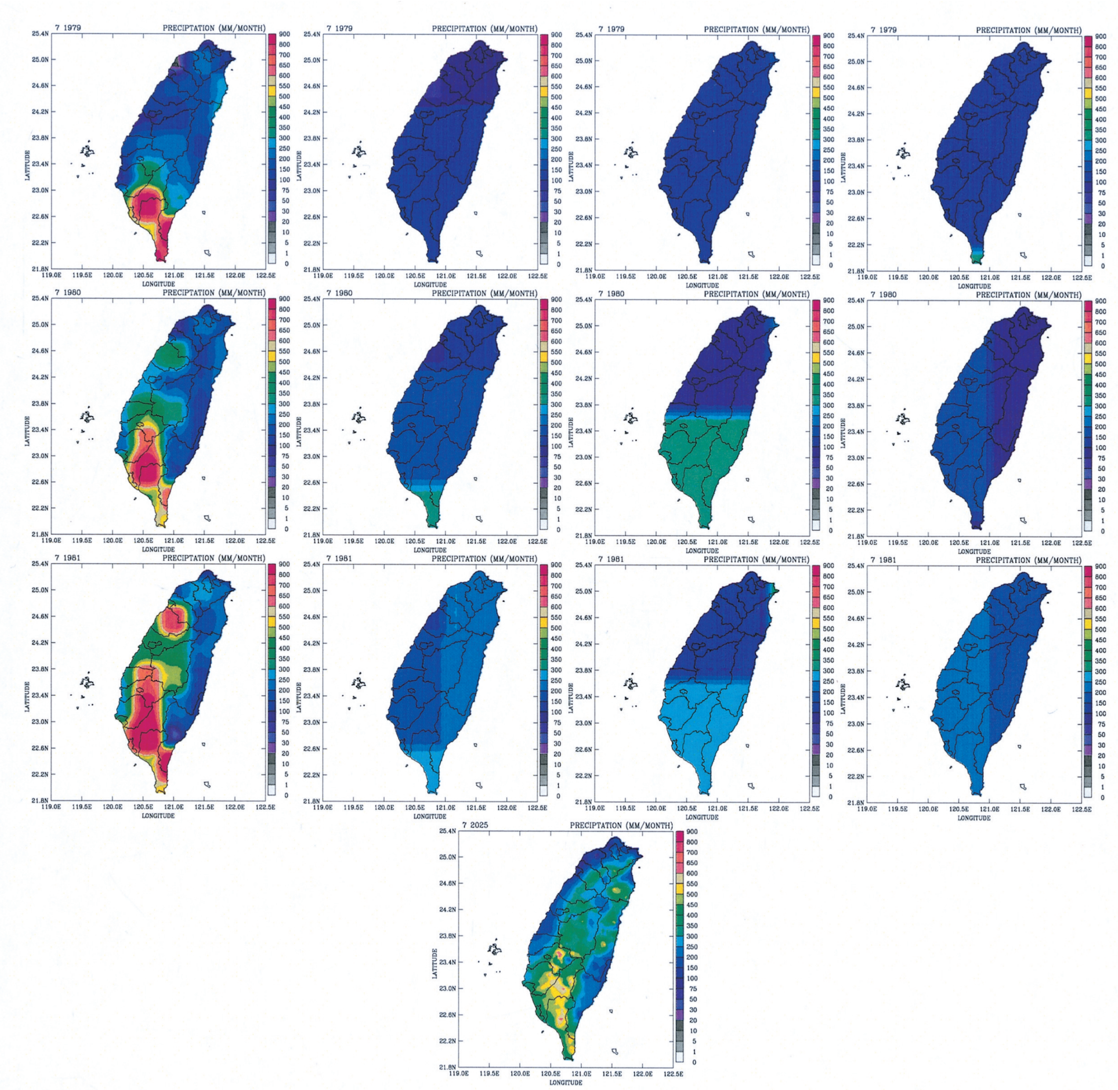

Fig. 11. The same as in Fig. 10 but for July.

reflects the combined effect of the southwesterly monsoon flow (abundant water vapor) and the north-to-south orientation of the mountain range in mechanically lifting the incoming monsoon flow so as to produce rainfall over the southern and southwestern areas of Taiwan (Chen and Chen 2003). These model-generated characters are consistent with the rainfall climatology shown in this figure.

As fall approaches, the PRECIS model produces comparatively more rainfall in the north and northeast of Taiwan than for other areas. This characteristic is consistent with field measurements (Chen and Chen 2003). However, the field measurements have more rainfall over the south and southeastern part of the country than does the PRECIS model. As the rainfall climatology is compiled based on 1992 - 2002 measurements, it is unclear how significant this change in flow pattern has been in September over the past twenty years. We have conducted a series of IMS Lagrangian model (Wang and Shallcross 2000) calculations for the period 1948 to 2002; and the variation in the flow pattern will be closely inspected in the analysis of the IMS Lagrangian results.

November is a climatologically dry season for the west and southwest parts of Taiwan, as these areas are on the lee side of the Central Mountain Range (Fig. 2a) during the winter monsoon season (Chen and Chen 2003). On the other hand, the windward side of the northern and eastern parts of Taiwan has abundant rainfall as evidenced through the field data. The PRECIS model clearly shows capability in reproducing these important characteristics. Though global models such as the CCSR and the NCEP are able to qualitatively show higher rainfall in the east than in the west, only the PRECIS model reproduces a complicated inhomogeneous rainfall distribution compatible with the field measurements. It is interesting to note that the CCSR appears to be able to show the east to west rainfall gradient more clearly than the HadCM3 in November, while the HadCM3 is able to demonstrate a more pronounced south to north rainfall gradient in July (Fig. 11) than the CCSR. This demonstrates the effect of grid arrangements as shown in Fig. 5. While both the CCSR and the HadCM3 have about 2 grids that divide Taiwan into two regions, the east-west division of grids in the CCSR enables the model to resolve the difference from west to the east. On the other hand, the south-north division of grids in the HadCM3 enables the model to discern the difference between the north and the south.

In summary, though Taiwan is not very large (400 km from north to south, and 150 km from east to west), surface rainfall measurements reveal very complicated patterns throughout the whole year. There is also clear evidence showing strong inter-annual variations in surface precipitation. This inter-annual variability is the biggest test of all climate models. As discussed previously and shown in Fig. 1b, Taiwan has maintained a longterm record of surface meteorological data for more than 100 years. Taiwan has also maintained one of the densest surface raingage station arrays in existence to measure an average annual rainfall of about 2500 mm. This places Taiwan in a unique position. It is well suited to the verification of quantitative precipitation prediction capability of all climate and weather models. We have developed a strong collaboration with the UK Hadley Centre at the Met Office to run the PRECIS model over the Taiwan area; and further collaboration on the use of the renowned Hadley Centre global climate model HadCM3 in Taiwan will further facilitate the verification of global climate modeling capability in Taiwan. The combined use of the Hadley Centre

PRECIS regional climate modeling system, and the Hadley Centre HADCM3 global climate modeling systems will enable the reconstruction of Taiwan's climate for the past 100 years. This capacity building will benefit both the Hadley Centre and Taiwan in the context of future climate change modeling and predictions in Taiwan and Asia in general.

3.5 Time Series Surface Temperature in Taipei, Taichung, and Kaohsiung

Figure 12 compares time-series temperature data from the field measurements in Taipei with that of the models. The PRECIS model underestimates temperature, while the NCEP

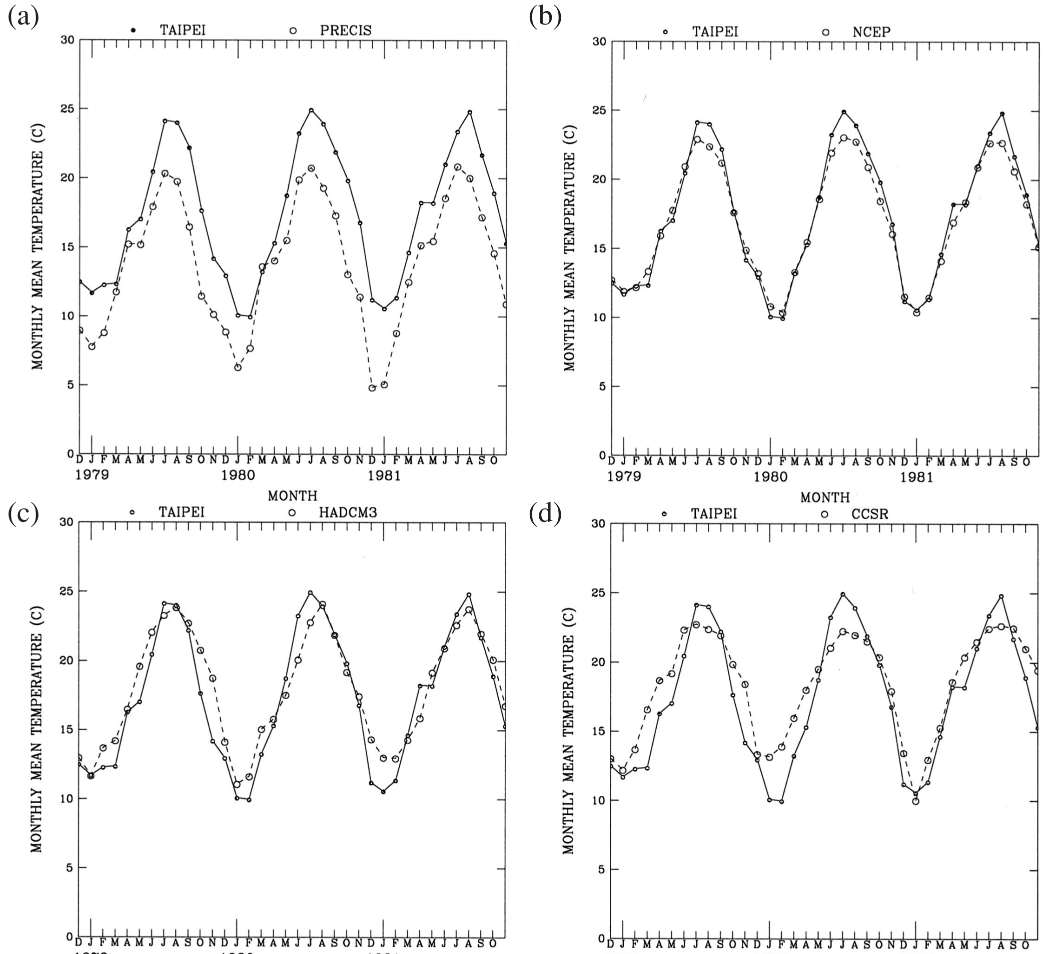

Fig. 12. Measured (solid circles) and modeled (open circles) time series plots of monthly mean surface temperature in Taipei for the period between December 1978 and November 1981. The modeled results are taken from PRECIS (a), NCEP (b), HADCM3 (c), and CCSR (d).

reanalyses are very close to the measurements. Both the HadCM3 and CCSR show close simulations of the measurements, though the 1979/1980 winter in the HadCM3, and the 1980/1981 winter temperatures in both the HadCM3 and CCSR are too high. In Taichung (Fig. 13), the PRECIS results are closer to the measurements than in Taipei, though the wintertime temperature is too high. The NCEP reanalysis temperatures are too low. The HadCM3 temperatures are generally close to the measurements except for the 1980/1981 winter when the model temperatures are too high. Interestingly, the CCSR winter temperatures are far too low. In Kaohsiung, (Fig. 14), the PRECIS and the HadCM3 perform similarly with both models having the 1980/1981 winter temperatures as warmer than the measurements. The NCEP summer

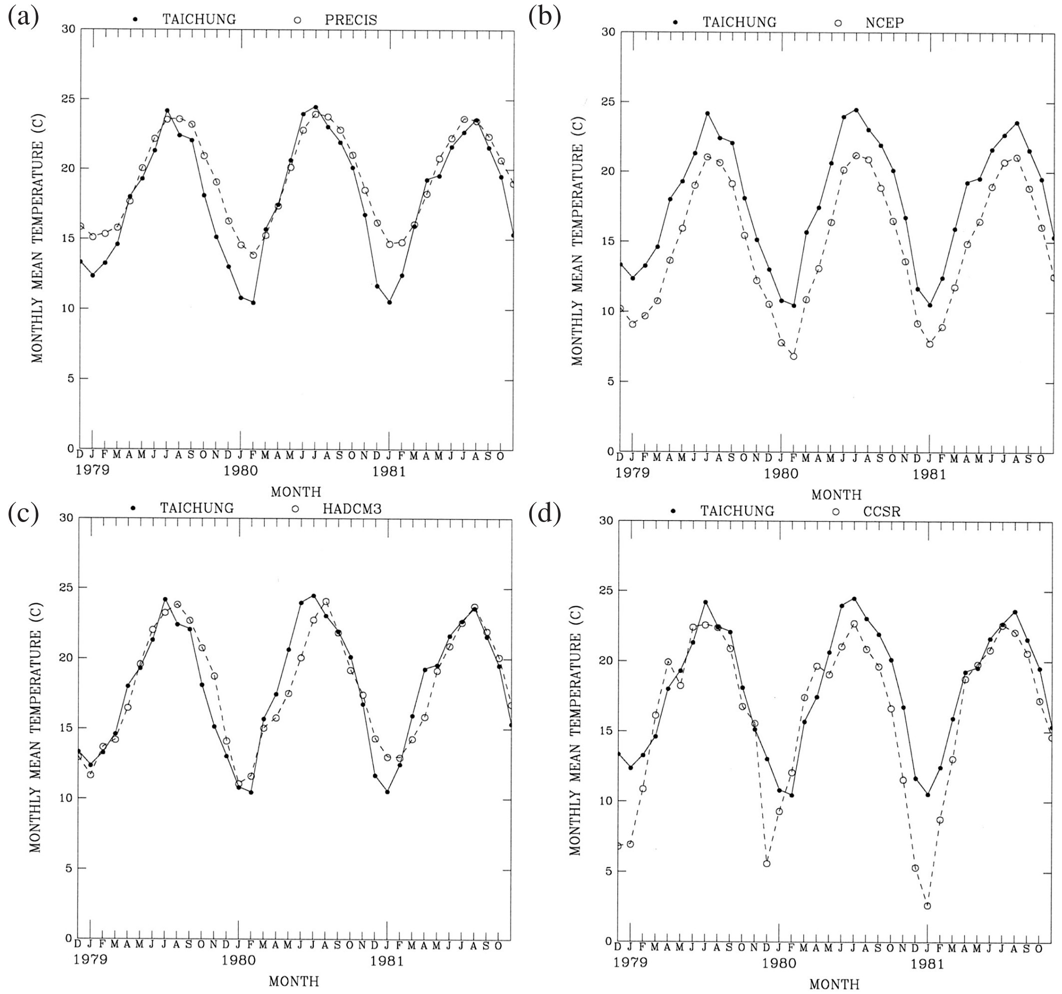

Fig. 13. The same as in Fig. 12 but for surface temperature in Taichung.

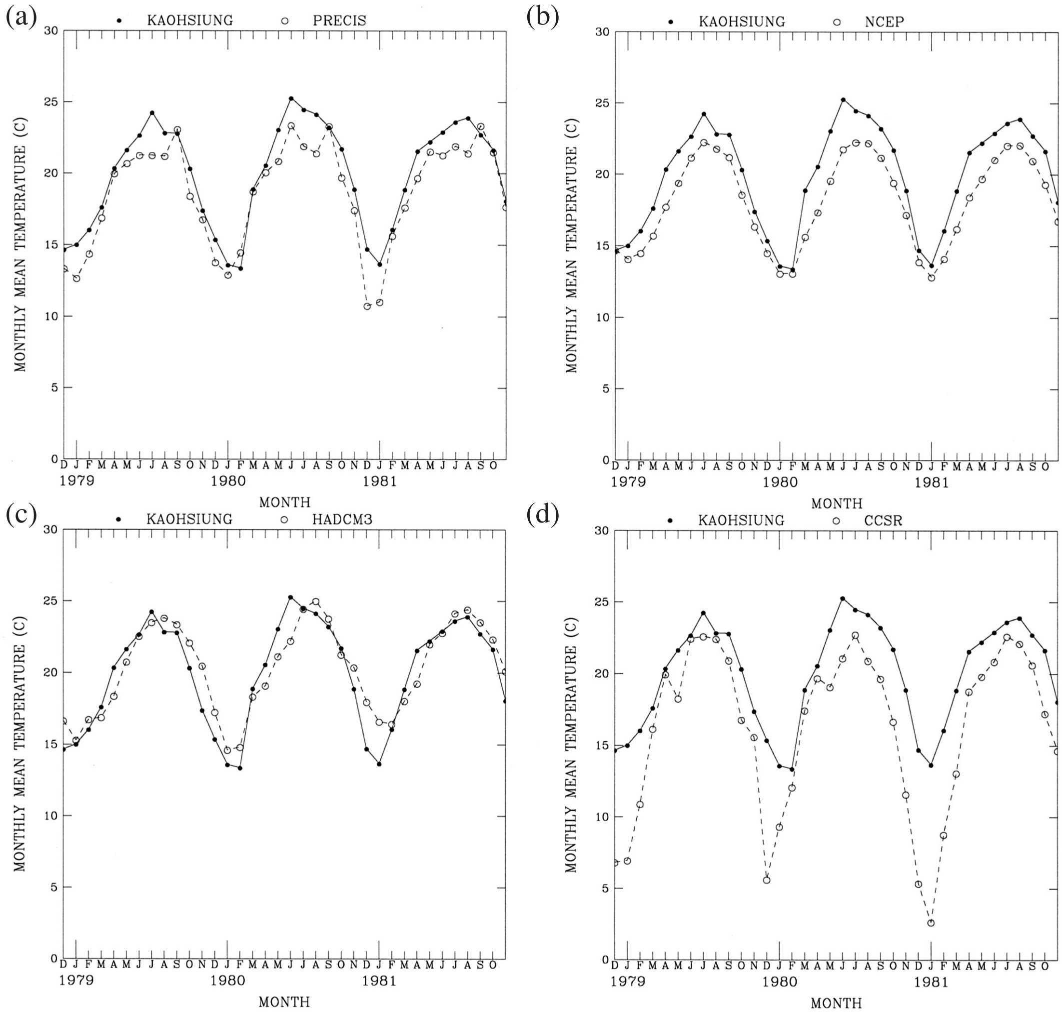

Fig. 14. The same as in Fig. 12 but for surface temperature in Kaohsiung.

temperatures are lower than the field data, and the CCSR temperatures are far too low. Generally speaking, except for the very cold winters produced by the CCSR model (the reasons are still unknown to us), there are fewer discrepancies in temperature than in precipitation simulations between these four models.

3.6 2-D Distribution of Surface Temperature over Taiwan

Comparisons in the previous section demonstrate a close resemblance between the PRE-

CIS model and global models. However, as comparisons are only made at sea level (the city sites), large discrepancies can occur if comparisons are made over the mountain regions, where global models are not able to resolve the effect of the topography.

Figure 15 shows a comparison of temperature distributions between the PRECIS model and the global models for January. As shown, low temperatures appear in the mountain region of Taiwan (Fig. 3a), while high temperatures exist only in the regions close to sea level and also close to the tropical lowland latitudes (e.g., southeast Taiwan). These complicated temperature patterns cannot be reproduced by the global models. There can be as much as a 20-degree difference in temperatures, as shown in the PRECIS calculations.

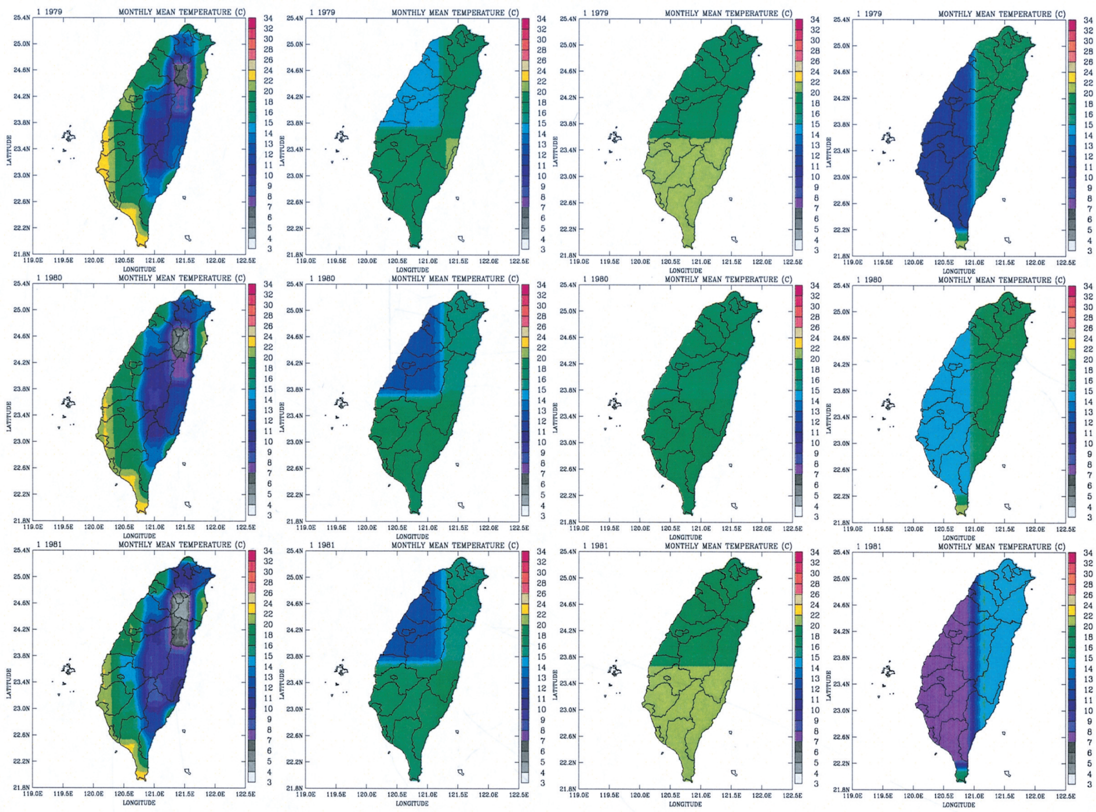

Fig. 15. The PRECIS simulations of surface temperature distributions in January of 1979, 1980, and 1981, respectively (plots in the 1st column from left). Also shown in the figure are the surface rainfall distribution from the NCEP reanalysis data (2nd column to the left), the HadCM3 simulations (3rd column to the left), and the CCSR simulations (4th column to the left).

In May, low temperatures in the mountain areas produced by the PRECIS model are not seen in the global models, though the global models can qualitatively show the north to south temperature gradients in this transient season (not shown here). In July, there is basically no temperature pattern at all from the global models, while the PRECIS model has reproduced the temperature reflecting the existence of the Central Mountain Range. As the seasons move toward winter, the large temperature difference between the mountain and low altitude regions reappears.

The above discussion clearly demonstrates the capability of the PRECIS model in reproducing surface temperature distributions that are closer to reality than those produced by the global models. As Taiwan is a mountainous country, the sustainable management of mountain forestry, agriculture (such as tea and fruit plantations), and preservation of the ecosystem are very important; the ability to predict future surface temperature in the mountains plays an important role in assessing climate impact over these areas of Taiwan.

4. SUMMARY AND DISCUSSION

In this paper we have evaluated climate simulations from three IPCC global climate models, and the Hadley Centre PRECIS regional climate model using high-resolution measurements of surface precipitations and temperature in Taiwan for the period between December 1978 and November 1981. We found that both global climate models and the PRECIS model show similar simulations on the monthly mean of surface temperature over areas at sea level (three cities shown here), while large discrepancies are found in the simulations of monthly accumulated surface rainfall. The regional climate model can reproduce month-to-month rainfall amounts and variations which more closely resemble the observed data than does NCEP reanalysis data over northern Taiwan; however, the PRECIS model appears to overestimate rainfall during the rainy season over southern Taiwan.

Since rainfall in Taiwan is influenced by southwesterly monsoon flows and typhoons during the warm season of May to August (Chen and Chen 2003), excessive rainfall in the PRECIS model over southern Taiwan is likely to be associated with these factors. Figure 16 compares modeled with observed daily rainfall in Kaohsiung. In July 1979, Typhoon Gordon tracked a path through the South China Sea and close to southern Taiwan during the 26^{th} - 29^{th}. The observed elevated rainfall during the 28^{th} - 29^{th} (Fig. 16a) reflects the influence of the southwesterly flow induced by the passing of Typhoon Gordon. The PRECIS model is able to simulate the occurrence of a tropical storm at a later time (31 July - 1 August), which bears more resemblance to the occurrence of Typhoon Hope. For the southwesterly flow without the influence of typhoons, the model shows rainfall greater than 20 mm day^{-1} during 8 - 24 July, while the observations only show rainfalls close to 20 mm day^{-1} on the days around the 10^{th} and 16^{th} - 18^{th}. This indicates that the PRECIS model is showing a more persistent southwesterly flow and inducing more active convective rainfall during this period than the observed data.

In July 1980, Typhoon Ida tracked a path through the South China Sea during the 8^{th} - 11^{th} (similar to Typhoon Gordon). The observed rainfall during this period (Fig. 16b) reflects the

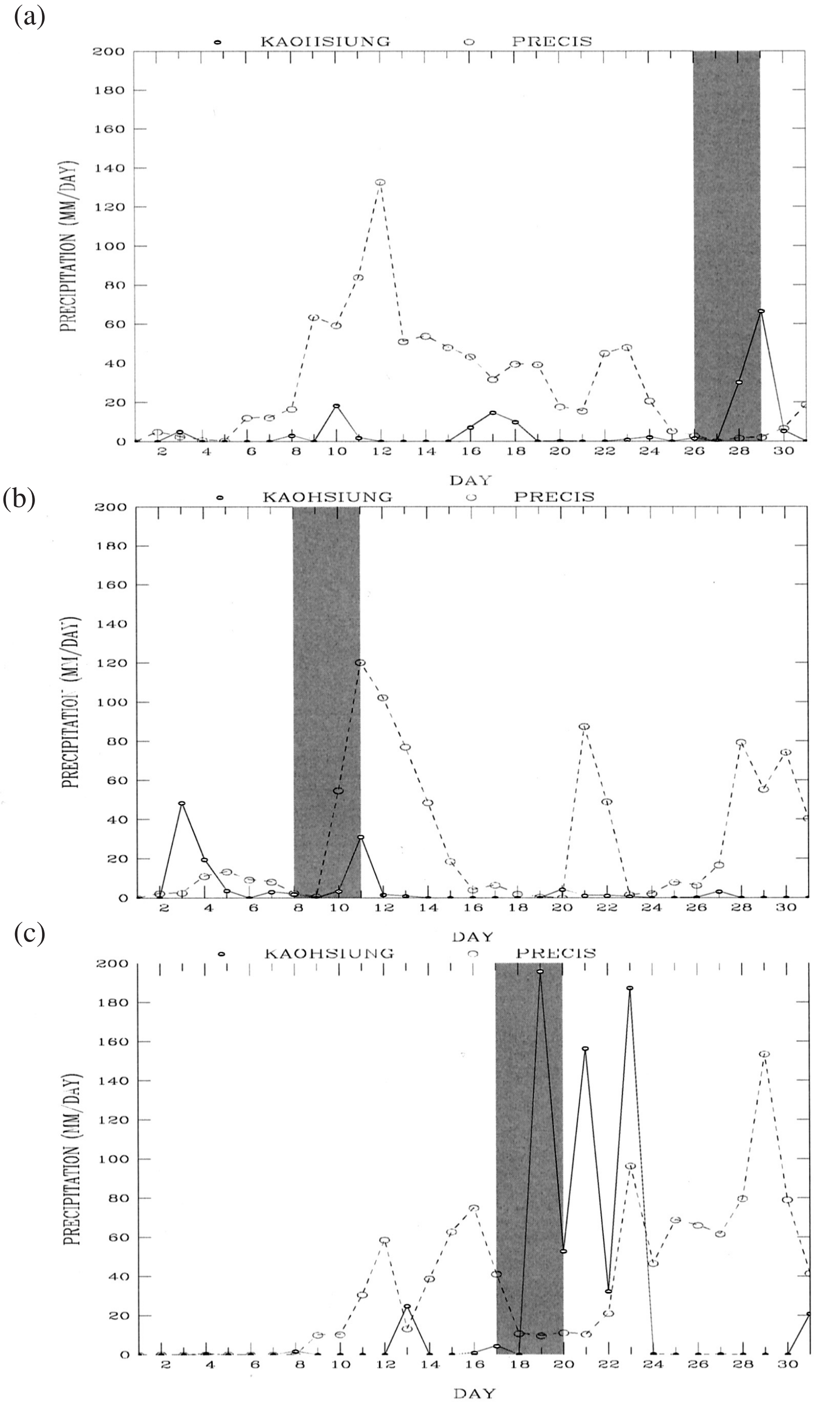

Fig. 16. Observed versus modeled daily rainfall in Kaohsiung during July of 1979 (a), 1980 (b), and 1981(c). Shaded areas indicate typhoon periods.

influence of this typhoon. The PRECIS model is able to reproduce a tropical storm during this period but with higher modeled rainfall and longer rainy days than the observations. During 20 - 22 August, the PRECIS model produces another tropical storm, not shown in observations, influencing Taiwan. The last period of strong and persistent southwesterly flow has been developed in the model again towards the end of this month. In July 1981, Typhoon Maury tracked a northwest path during 17 - 20 July. Intensive rainfalls observed during 19 - 23 July (Fig. 16c) indicate the influence of this typhoon. The PRECIS model is able to predict a tropical storm influencing Taiwan during 20 - 24 July, and a more persistent southwesterly flow than the observations after the passing of the typhoon.

Hence, the anomalously rigorous and persistent southwesterly flow during the summer months over southern Taiwan, and the occurrence of typhoons and the southwesterly flows induced by the passing of typhoons are the main causes of excessive rainfall produced by the model. These are two areas which require further work in the future. Sources of excessive rainfall simulation produced by the PRECIS model over other regions have been identified. These including inadequate regional physics, excessive supply of moisture from lateral boundaries, inadequate representations of local forcing, circulation errors in the driving global models, and circulation errors in the regional climate model (Noguer et al.1998; Jones et al. 1995). Recently, Wang et al. (2004) has suggested that cloud-radiation interactions can play an important role in the evolution of the East Asian summer monsoon processes.

We conclude that the PRECIS model is well suited for modeling Taiwan's climate. More modeling studies are needed to further establish the strength and weakness of the model, especially the capability of the model in reproducing storminess over the Pacific (e.g., Weisse et al. 2005). As demonstrated in this work, the use of the PRECIS regional climate model with output from the ERA-15 reanalysis data provides incisive results for understanding Taiwan's climate, which is strongly influenced by the Asian monsoons and typhoons (Fig. 17).

To further demonstrate the need for high-resolution regional climate modeling, Fig. 17 shows monthly August rainfall in Taiwan from 1992 to 2002. During these 11 years, 1993, 1995, 2001, and 2002 are clearly drier than the other years. The climatology of these 11 years (Fig. 17) is certainly useful. However, it is the inter-annual variability in rainfall from year to year that is the issue we need to address for the past and, more importantly, into the future.

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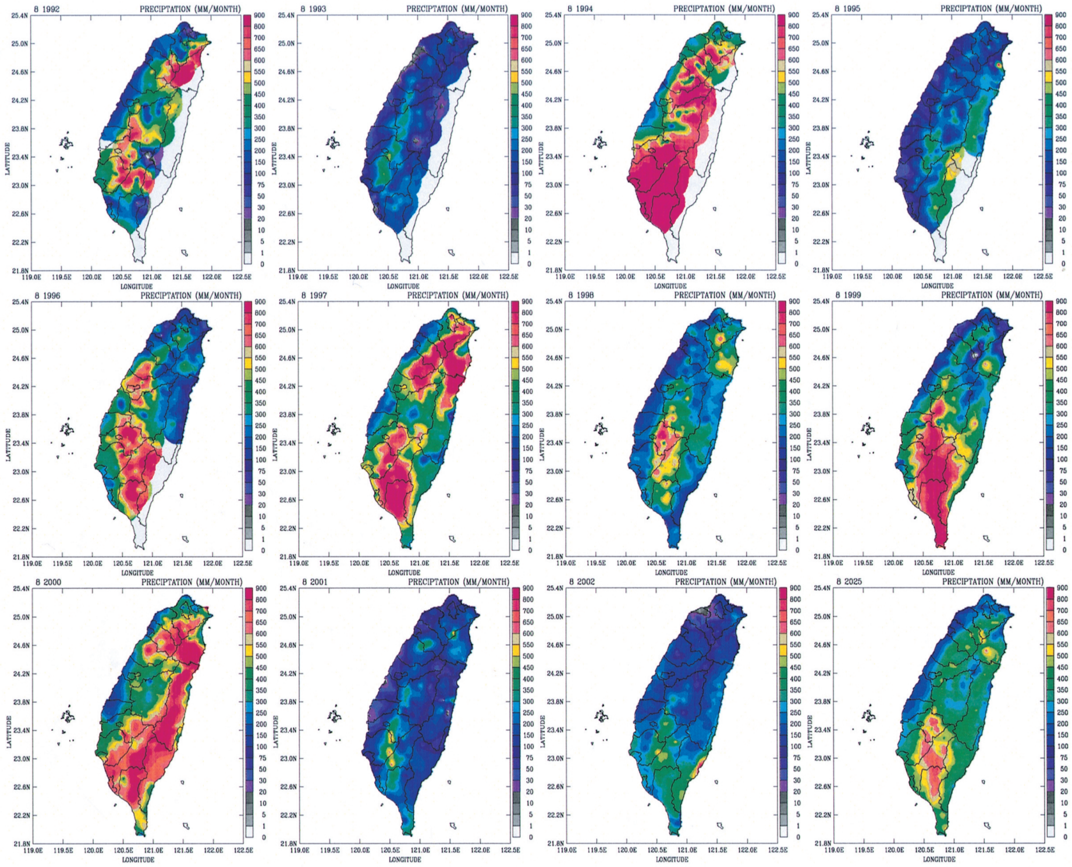

Fig. 17. Monthly August rainfall in Taiwan from 1992 to 2002. Read 8 1992 as August 1992. The last panel (indicated by 8 2025) shows the mean of 1992 - 2002.

REFERENCES

Arakawa, A., and V. R. Lamb, 1977: Computational design of the basic dynamical processes of the UCLA general circulation model, in Methods in Computational Physics, 17. In: Chang, J. (Ed.), Academic Press, New York, 173-265.

Bhaskaran, B., J. M. Murphy, and R. G. Jones, 1998: Intraseasonal oscillation in the Indian summer monsoon simulated by global and nested regional climate models. *Mon. Wea. Rev.*, **126**, 3124-3134, .

Burroughs, W., 2003: Climate into the 21st century, World Meteorological Orginization. Cambridge Univ. Press.

Chen, C. S., and Y. L. Chen, 2003: The rainfall characteristics of Taiwan. *Mon. Wea. Rev.*, **131**, 1323-1341.

Chen, G. T. J., C. C. Wang, and S. C. S. Liu, 2003: Potential vorticity diagnostics of a Mei-Yu front case. *Mon. Wea. Rev.*, **131**, 2680-2696.

Collier, M., and R. H. Webb, 2002: Floods, droughts, and climate change. Univ. Arizona Press.

Cox, P. M., R. A. Betts, C. B. Bunton, R. L. H. Essery, P. R. Rowntree, and J. Smith, 1999: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Clim. Dyn.*, **15**, 183-203.

Deutsch, C. V., and A. G. Journel, 1992: GSLIB: Geostatistical Software Library and Users Guide. Oxford C Univ. Press, New York.

Durman, C. F., J. M. Gregory, D. C. Hassell, R. G. Jones, and J. M. Murphy, 2001: A comparison of extreme European daily precipitation simulated by a global and a regional climate model for present and future climates. *Q. J. R. Meteor. Soc.*, **127**, 1005-1015.

Emori, T. Nozawa, A. Abe-Ouchi, A. Numaguchi, M. Kimoto, and T. Nakajima, 1999: Coupled ocean-atmospheric model experiments of future climate change with an explicit representation of sulfate aerosol scattering. *J. Meter. Soc. Jpn.*, **46**, 1299-1307.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T.C. Johns, J. F. B. Mitchell, and R. A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustment. *Clim. Dyn.*, **16**, 147-168.

Gregory, D., and P. R. Rowntree, 1990: A mass-flux convection scheme with representation of cloud ensemble characteristics and stability dependent closure. *Mon. Wea. Rev.,* **118**, 1483-1506.

Gregory, D., and S. Allen, 1991: The effect of convective downdraughts upon NWP and climate simulations, in Ninth Conference on Numerical Weather Prediction. Denvor, Colorado, 122-123.

Gregory, D., R. Kershaw, and P. M. Inness, 1997: Parameterization of momentum transport by convection II: Tests in single column and general circulation models. *Q. J. R. Meteor. Soc.*, **123**, 1153-1183.

Hsu, H. H., and C. T. Chen, 2002: Observed and projected climate change in Taiwan, Meteorol. *Atmos. Phys.*, **79**, 87-104.

Hulme, M., G. J. Jenkins, X. Lu, J. R. Turnpenny, T. D. Mitchell, R. G. Jones, J. Lowe, J. M. Murphy, D. Hassell, P. Boorman, R. McDonald, and S. Hill, 2002: Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, Univ. East Anglia, UK, 120 pp.

Huntingford, C., R. G. Jones, C. Prudhomme, R. Lamb, J. H. C. Gash, and D. A. Jones, 2003: Regional climate-model predictions of extreme rainfall for a changing climate. *Q. J. R. Meter. Soc.*, **129**, 1607-1621.

IPCC, Climate Change, 2001: Impacts, adaptations and vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. In: McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken, and K. S. White (Eds.), Cambridge Univ. Press, Cambridge, UK.

Jones, R. G., J. M. Murphy, and M. Noguer, 1995: Simulation of climate change over Europe using a nested regional-climate model. I: Assessment of control climate, including sensitivity to location of lateral boundaries. *Q. J. R. Meteor. Soc.*, **121**, 1413-1449.

Jones, R. G., J. M. Murphy, M. Noguer, and A. B. Keen, 1997: Simulation of climate change over Europe using a nested regional-climate model. II: Comparison of driving and regional model responses to a doubling of carbon dioxide. *Q. J. R. Meteor. Soc.*, **123**, 265-292.

Jones, R., D. Hassell, D. Hudson, S. Wilson, G. Jenkins, and J. Mitchell, 2003: Workbook on generating high resolution climate change scenarios using PRECIS, Hadley Centre for Climate Prediction and Research, Met Office, Bracknell, UK.

Jones, R. G., M. Noguer, D. C. Hassell, D. Hudson, S. S. Wilson, G. J. Jenkins, and J. F. B. Mitchell, 2004: Generating high resolution climate change scenarios using PRECIS, Met Office Hadley Centre, Exter, UK, 40 pp.

Kaiser, M., 2002: How the weather affects your health, Michelle Anderson Publishing Pty Ltd, Melbourne.

Kalnay, E., et al. 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.*, **77**, 437-471.

Martens, P, 1998: Health and climate change, Earthscan Publications Ltd, London, 1998. Noguer, M., R. Jones, and J. Murphy, Sources of systematic errors in the climatology of a regional climate model over Europe. *Clim. Dyn.*, **14**, 691-712.

Ohfuchi, W., H. Nakamura, M.K. Yoshioka, T. Enomoto, K. Takaya, X. Peng, S. Yamane, T. Nishimura, Y. Kurihara, and K. Ninomiya, 2004: 10-km mesh meso-scale resolving simulations of the global atmosphere on the Earth Simulator - Preliminary outcomes of AFES (AGCM for the Eath Simulator). *J. Earth Simulator*, **1**, 8-34.

Palmer, T. N., G. J. Shutts, and R. Swinbank, 1986: Alleviation of a systematic westerly bias in general circulation and numerical weather prediction models throught an orographic gravity wave drag parameterization. *Q. J. R. Meteor. Soc.*, **112**, 1001-1039.

Simmons, A. J., and J. K. Gibson, 2000: The ERA-40 project plan, ERA-40 Project Report Series No. 1, Reading, U.K., 62 pp.

Smith, R. N. B., 1990: A scheme for predicting layer clouds and their water content in a general circulation model. *Q. J. R. Meteor. Soc.*, **116**, 435-460.

Sui, C. H., C. Y. Huang, Y. B. Tsai, C. S. Chen, P. L. Lin, S. L. Shieh, M. H. Li, Y. A. Liou, T. C. Wang Chen, R. S. Wu, G. R. Liu, and Y. H. Chu, 2002: Meteorology-hydrology study targets typhoon Nari and Taipei flood. *EOS*, **83**, 265.

Wang, K. Y., and D. E. Shallcross, D. E., 2000: A Lagrangian study of the three-dimensionaltransport of boundary-layer tracers in an idealised baroclinic-wave life-cycle. *J. Atmos. Chem.*, **35**, 227-247.

Wang, K. Y., D. E. Shallcross, P. Hadjinicolaou, and C. Giannakopoulos, 2004: Ambient vehicular pollutants in the urban area of Taipei: Comparing normal with anomalous vehicle emissions. *Water, Air, Soil Pollut.*, **156**, 29-55.

Wang, W. C., W. Gong, W. S. Kau, C. T. Chen, H. H. Hsu, and C. H. Tu, 2004: Characteristics of cloud radiation forcing over East China. *J. Clim*, **17**, 845-853.

Weisse, R., H. von Sotrch, and F. Feser, 2005: Northeast Atlantic and North Sea storminess as simulated by a regional climate model 1958-2001 and comparison with observations. *J. Clim.*, **18**, 465-479.